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Seismic analysis of turbo machinery foundation: Shaking table test and computational modeling

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Abstract. Foundation plays a significant role in safe and efficient turbo machinery operation. Turbo machineries generate harmonic load on the foundation due to their high speed rotating motion which causes vibration in the machinery, foundation and soil beneath the foundation. The problems caused by vibration get multiplied if the soil is poor. An improperly designed machine foundation increases the vibration and reduces machinery health leading to frequent maintenance. Hence it is very important to study the soil structure interaction and effect of machine vibration on the foundation during turbo machinery operation in the design stage itself. The present work studies the effect of harmonic load due to machine operation along with earthquake loading on the frame foundation for poor soil conditions. Various alternative foundations like rafts, barrette, batter pile and combinations of barrettes with batter pile are analyzed to study the improvements in the vibration patterns. Detailed computational analysis was carried out in SAP 2000 software; the numerical model was analyzed and compared with the shaking table experiment results. The numerical results are found to be closely matching with the experimental data which confirms the accuracy of the numerical model predictions. Both shake table and SAP 2000 results reveal that combination of barrette and batter piles with raft are best suitable for poor soil conditions because it reduces the displacement at top deck, bending moment and horizontal displacement of pile and thereby making the foundation more stable under seismic loading.

Keywords: turbo machinery; raft; barrette; batter pile; dynamic loading; computational analysis

1. Introduction

Turbo machineries are generally installed on the foundation top deck while the auxiliary equipment such as condensers and pipes are installed below the deck. As the turbo machineries are heavy duty items, the foundation should have sufficient strength to support the turbo-machine and its auxiliary equipment and also should be designed to limit the vibration amplitudes arising due to the rotating machineries at top deck. Due to very high speed of the rotatory machines even small magnitude of vibrations in the top deck induces cracks in the top-deck and reduces the efficiency of the whole foundation.

In the case of poor soil conditions, frame foundations experience higher vibration amplitude at raft level resulting in higher harmonic loads into the structure and thereby weakening the structural strength. The natural calamity like earthquake can have severe effect on the whole structure if the frame foundation has not been properly designed. Hence proper care should be taken while designing the frame foundation in poor soil and earthquake prone areas.

The soil response influences the structure motion and vice versa which is termed as soil-structure interaction (Kramer 1996). (Fattah *et al.* 2014) studied the dynamic loading in the dynamic analysis of foundations based on the fully saturated sandy soil using the finite element method by QUAKE/W computer program. Lakshmanan *et al.* (2009) performed dynamic analysis of framed foundations supporting high speed machines. In poor soil conditions the use of raft, barrettes, batter pile are the best options for frame foundations. Frame foundation with pile significantly reduces the vibrations compared to raft (Rajkumar *et al.* 2014). However combined pile raft foundation shows adverse conditions on complex soil structure interaction under static, pseudo static, and different earthquake loading (Kumar *et al.* 2016). The role of the barrettes, batter piles usually considered useful to the structural system under dynamic loading because it increases the durability of the structure (Pastsakorn *et al.* 2002). A barrette is a cast-in-place reinforced concrete column which can be used instead of conventional piles. Barrettes, can overcome all the disadvantages of using the pile. Load (vertical and lateral) resisting capacities are very high in barrettes and therefore a single barrette can replace a few conventional piles, resulting in savings in construction time, quantity of concrete and steel, size of pile caps, etc. (Ramaswamy and Pertusier 1986). Batter piles offer large stiffness and bearing capacity compared to vertical piles on soft soils because of its inclined installation (Ghazavi *et al.* 2014). Batter piles resist lateral load from earthquake, soil pressure, and transmit the applied lateral load in axial direction. The strength of the batter pile constructed in medium or dense sand increases with the increase of batter angle, attains

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maximum value at 20° and then decreases. (Giannakou *et al.* 2010).

There are several options for modeling the soil-pile structure interaction for both static and dynamic loads such as the pile are modeled as pile springs (Nazir *et al.* 2013), as beams and columns with frame elements (Liu 2013). The spring constants include vertical, horizontal, rocking, cross-stiffness, and torsion (Liu 2013).

Fattah *et al.* (2015a) investigated the effect of the foundation geometry on the dynamic response of machine foundation using ANSYS software. They have reported that as the pile diameter increases, the frequency at which the maximum displacement occurred also increases, and hence the system becomes more stable against resonance at larger pile diameters. Fattah *et al.* (2015b) carried out dynamic analysis of a machine foundation using PLAXIS 2D with different embedment depth at saturated sand. They have reported that increase in the embedment ratio causes a reduction in the dynamic response; but, when the depth of embedment increases higher than 1m, the effect become less pronounced and as strength of the soil also increases. Tripathy and Desai (2016) studied the effect of raft, pile with raft and barrettes with raft subjected to harmonic load on the turbo-generator foundation in medium dense and partially saturated sand. They have carried out both experimental and numerical analysis and reported that the displacement at top deck is lower for barrettes compared to raft and pile structures. Nguyen *et al.* (2016) investigated the influence of shallow foundation size on the seismic response of a regular mid-rise moment resisting building frame during earthquake excitations. They have found that larger shallow foundations can moderate the amplifications of lateral deflection and in turn inter-story drifts of the structure caused by Soil Foundation Structure Interaction (SFSI). When the foundation sizes were reduced, the spectral acceleration started to decrease considerably as the natural period lengthened and consequently, there was a significant reduction in the base shears. Hence, structures with smaller shallow foundation sizes are recommended, as they attract less shear forces and thus the level of damage to a structure would be less in case of strong earthquakes. Hokmabadi and Fatahi (2015a) carried out parametric analysis on a 15-storey full-scale (prototype) structure with different types of foundations including a fixed base, a shallow foundation, a floating pile foundation, and a pile-raft foundation using FLAC3D software. The results of this study indicated that the structure supported by the pile-raft foundation and the floating pile foundation experienced more base shear compared to the structure supported by the shallow foundation. However, the structure supported by shallow foundation experienced the most severe rocking followed by floating pile and pile-raft foundations because the pile elements in both foundations reduced the maximum uplift and the rocking experienced by the structures. In case of floating pile foundation, as the compressive stresses generated in one side of the foundation, piles experienced more settlement compared to the pile-raft foundation where the compressive stresses were distributed over a larger area, which in turn, reduced the settlement. Hence they concluded that the type of foundation is a major contributor to the seismic response of buildings with SSI and should therefore be given careful consideration in order to ensure a safe and cost effective design.

Hokmabadi *et al.* (2015b) conducted series of shaking table tests providing scaled earthquakes to the structure and proved that pile foundations are better than raft for soft soil. Fattah *et al.* (2016a, b) investigated dynamic response of machine foundations by conducting experiments with physical models. They have concluded that the final settlement of the foundation increases with increasing the amplitude of dynamic force, operating frequency and degree of saturation. However, it decreases with increasing the relative density of sand, modulus of elasticity and soil embedment. Fattah *et al.* (2016c) studied the dynamic response of piles to lateral shaking in order to predict the lateral dynamic responses of foundations in sandy soil under earthquake loading. Pitilakis *et al*. (2008), Haeri *et al.* (2012), Su *et al.* (2016) have reported larger bending stiffness, decrease in frequency and increase in amplitude for piles upon earthquake excitation by conducting shake table experiment.

In the current work, soil structure interaction with rafts, barrettes, batter piles have been studied by conducting experiments in shake table with input of scaled real earthquakes and numerical analysis in SAP 2000 software. Following four cases have been considered for conducting the experiment viz: The turbo generator foundation supported by (i) raft, (ii) raft with barrettes, (iii) raft with batter pile (iv) raft with barrettes and batter pile. All the above four cases were also analyzed by computational modeling in SAP 2000. The numerical model was analyzed and compared with the experimental results.

2. Material properties, experimental and analytical study

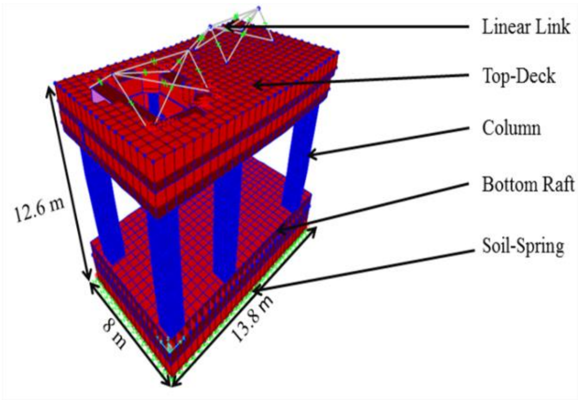
2.1 Soil properties

The soil used for this study is sandy soil which consists of two layers, i.e., top and bottom layer. Both the layers of soil have specific gravity 2.61 measured according to ASTM D854 standard. The sand which are passed in 2.0 mm and retained in 0.425 mm sieve was taken for the research work. Minimum and maximum dry unit weights of sand for top layer are maintained as 16.5 and 13.75 kN/m^3 respectively. The effective grain size (D50), coefficient of uniformity (Cu) and coefficient of gradation (Cc) of the top layer sand are 0.75 mm, 2.0, and 1.01 respectively. For bottom layer the minimum and maximum dry unit weight of sand are maintained as 17.5 and 14.3 kN/m^3 respectively.

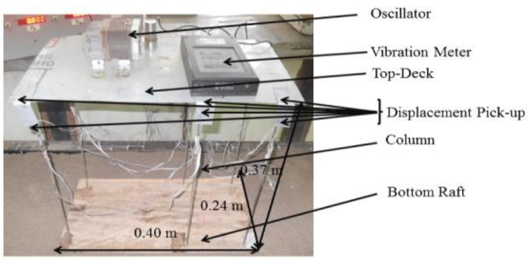
Similarly, the effective grain size (D10), coefficient of uniformity (Cu) and coefficient of gradation (Cc) of the bottom layer sand are 0.14 mm, 1.78 and 1.03 respectively. The relative density of the sand beds for both layers is maintained as 18%.

2.2 Foundation properties

Model tests replicate the boundary conditions of an



(a) Real model prototype in SAP 2000



(b) Scaled Physical Model(1:34)

Fig. 1 Turbo generator foundation model

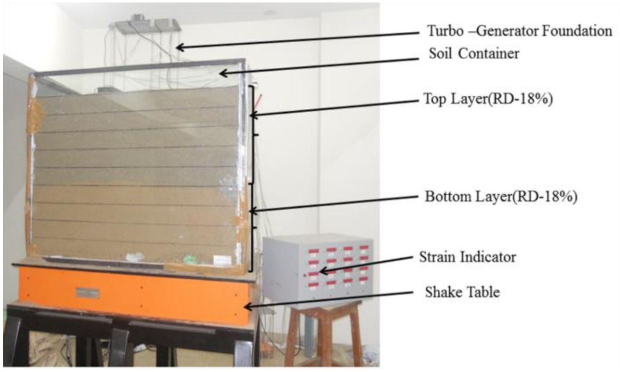


Fig. 2 Turbo generator foundation model with shaking table experiment

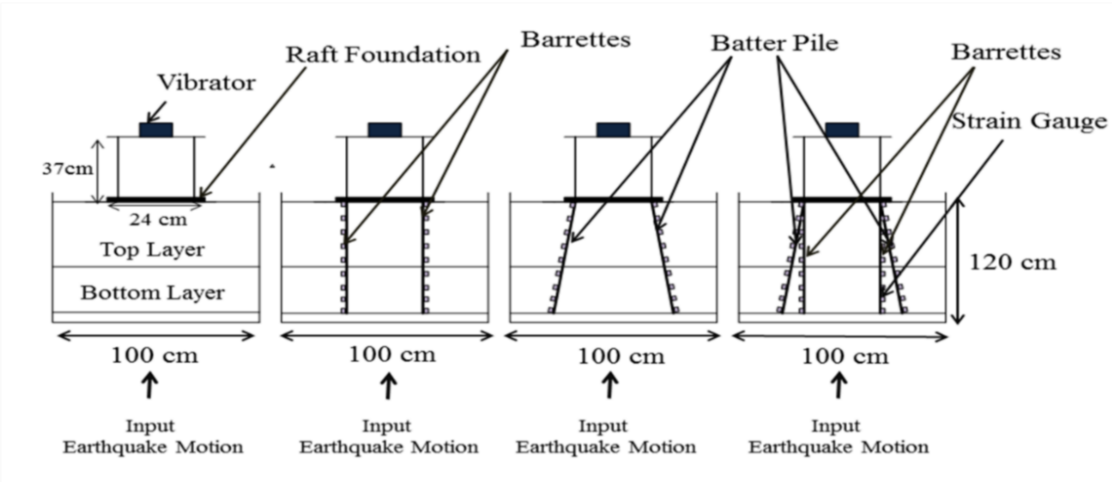
actual problem by subjecting a small-scale physical model of a full-scale prototype structure providing the opportunity of better understanding the fundamental mechanisms of these systems (Hokmabadi *et al.* 2014). In-line with this approach, a turbo-generator foundation of length 13.8 m, width 8 m and height of 12.6 m consisting of three transverse frames, with a top deck and bottom raft designed by Dr. KG Bhatia Bhatia (2009) has been considered as a reference prototype in the current study. The experimental model has been prepared by applying a geometric scaling factor of 1:34 to the above published model dimensions which is found to be 0.40 m×0.24 m×0.37 m (L×B×H) respectively. The dimension and material of Turbo generator foundation are shown in Table 1. Fig. 1 shows the real model prototype of turbo generator foundation considered in this study and the physical model scaled with a factor of 1:34.

Table 1 Foundation properties

MATERIAL	MATERIAL PROPERTIES	UNIT
FOUNDATION Top Deck(23×40) cm^2		
Unit weight, *γ*	77	kN/m^3
Young's modulus, *E*	2.1×10^8	kN/m^2
Poisson's ratio, *ν*	0.3	
Beam (0.5×0.5) cm^2		
Unit weight, *γ*	77	kN/m^3
Young's modulus, *E*	2×10^8	kN/m^2
Poisson's ratio, *ν*	0.3	
Column(Circular Section) 0.4 cm Dia.		
Unit weight, *γ*	77	kN/m^3
Young's modulus, *E*	2×10^8	kN/m^2
Poisson's ratio, *ν*	0.3	
Raft (24×40) cm^2		
Unit weight, *γ*	7.8	kN/m^3
Young's modulus, *E*	10×10^6	kN/m^2
Poisson's ratio, *ν*	0.4	
Pile(Circular Section) 0.6 cm Dia.		
Unit weight, *γ*	7.8	kN/m^3
Young's modulus, *E*	10×10^6	kN/m^2
Poisson's ratio, *ν*	0.4	
MACHINE	0.750	kg

2.3 Experimental setup

Shake Table was used for investigating the harmonic loading on the prepared turbo generator foundation model with earthquake excitation in the Structural Dynamics Laboratory of Applied Mechanics Department at SVNIT Surat, India. The dimensions of the shake table used in this study are 2 m×1 m. The picture of the physical turbo generator foundation model with shake table is shown in Fig. 2. The test tank was filled with sand in layers of 10 cm from a fixed height by sand raining technique to achieve relative density of 18%. The test tank used in this research has dimensions of 2 m length, 1.0 m width and 1.2 m height. As the test tank is a rigid container, it can be noted that the response of the model could be affected by the boundary conditions and hence it is preferred to have flexible containers. However, during the experiment it is



(a) Model supported by raft foundation

(b) Model supported raft with barrettes

(c) Model supported raft with batter pile

(d) Model supported raft with barrettes and batter pile

Fig. 3 Line diagram of the experimental model

Table 2 Earthquake motions obtained from PEER

Earthquake	Country	Year	Magnitude	Type	Peak Ground Acceleration (PGA(g))
Northridge Earthquake	USA	1994	6.4	Near Field	0.901
Napa Earthquake	USA	2014	6.0	Near Field	0.611
El-Centro Earthquake	USA	1940	6.9	Far Field	0.359
Chile Earthquake	Chile	2015	8.3	Far Field	0.272

observed from the top as well as the side of the model that such boundary effects are negligible. The schematics of the experimental model dimensions for the raft, barrette and batter piles and barrettes with batter pile are explained in Fig. 3.

After installation of model barrette/batter pile, model raft was connected to each pile/barrette by nuts. Then upper part of the model (consisting of top deck, column and beam) placed over the raft connecting with each other. A vibrator of 1600 rpm was fixed at top deck of the foundation. The vibrating motor cause's periodic dynamic forces $F(t)$ which can be given below

$$F(t)=A\sin\omega(t) \tag{1}$$

Where, a=maximum amplitude of dynamic force, $\omega=2\pi f$ with f=operating frequency, t=time.

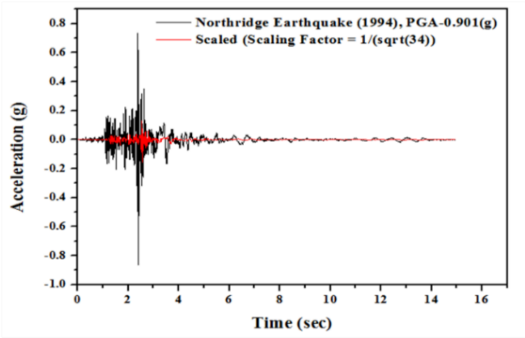
A vibration meter (make ABRO, model MV-410) was used in the experiment to record the vibration measurements at top deck. Top deck displacement values were measured by the attached displacement pickups. Shake table tests were conducted by applying scaled earthquake acceleration for North ridge Earthquake (1994), Napa earthquake (2014), Chile earthquake (2015) and El-Centro earthquake (1940) to the scaled turbo generator foundation model. The length of the model piles is considered as 90 cm, which is placed just below the columns. The working frequency of the table ranges from 1 to 50 Hz with a load of 10 ton. Nine pairs of strain gauges were attached to the barrettes/batter to measure the bending strain while conducting the experiment. Accelerometer has been attached to top deck and bottom raft to measure accelerations. The tests were repeated several times to examine the performance of the experimental model, the reliability of the system and also to verify the consistency of test data.

2.4 Shake table study

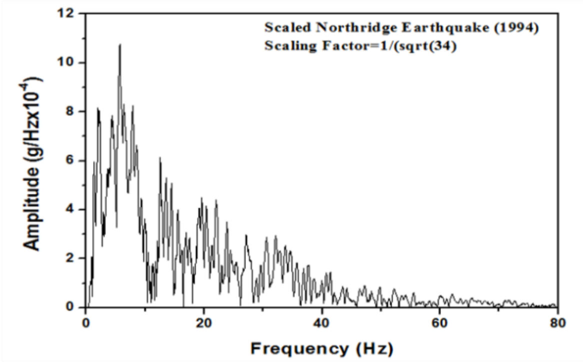
The peak ground acceleration values for real earthquakes in this study are taken from the published data in Pacific Earthquake Engineering Research (PEER) website (2016), which are summarised in Table 2. Each test model is subjected to two near field shaking events (Napa 1994 and Northridge, 2014) and two far field earthquakes (El-Centro and Chile). Intensity of shaking decreases as the distance increases from the epicentre of the seismic fault. Additionally, high frequency components lose energy more quickly than low frequency components while travelling through the ground (Towhata 2008). Hence, near field earthquakes generate higher peak ground acceleration and frequency compared to far field earthquakes. The selected earthquakes in this study cover wide range of magnitudes and peak ground accelerations and thus making the study more comprehensive and conclusive for different types of earthquake loadings. Fig. 4 shows the input acceleration and dominant frequency applied at the base of the soil model for experimental and numerical model.

2.5 Computer program SAP 2000

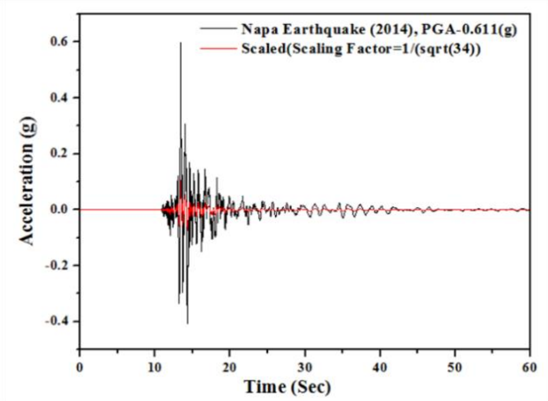
The software used in current work for the computational analysis is SAP 2000 v18. Shell, and frame elements are used to represent the top-deck, beam, columns, and raft. Soil has been designed as a solid media with proper



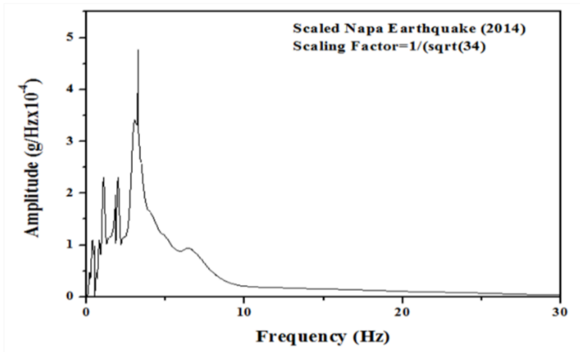
(a) Time history for Northridge Earthquake



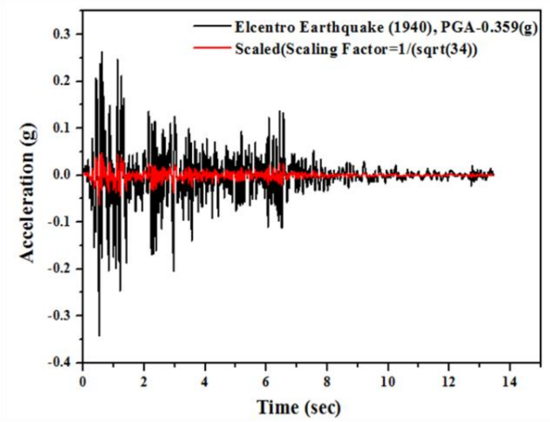
(b) Fourier transform for Northridge Earthquake



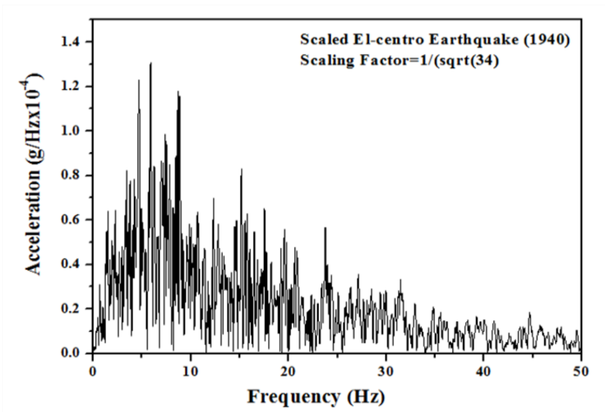
(c) Time history for Napa Earthquake



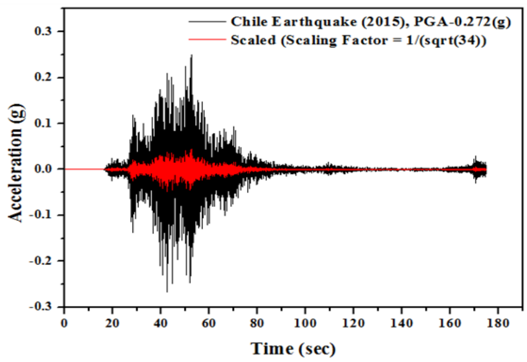
(d) Fourier transform for Napa Earthquake



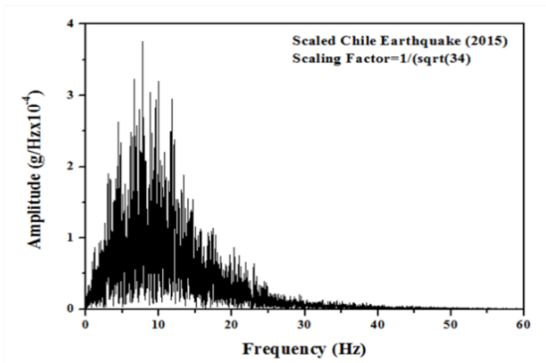
(e) Time history for El-Centrino Earthquake



(f) Fourier transform for El-Centrino Earthquake

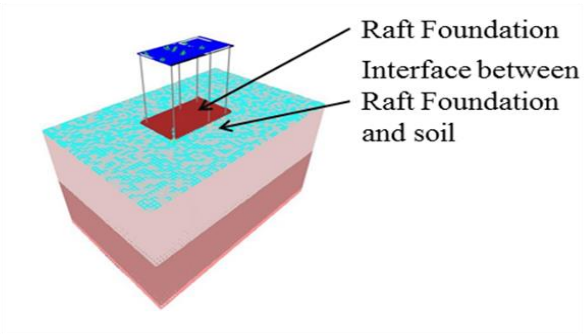


(g) Time history for Chile Earthquake

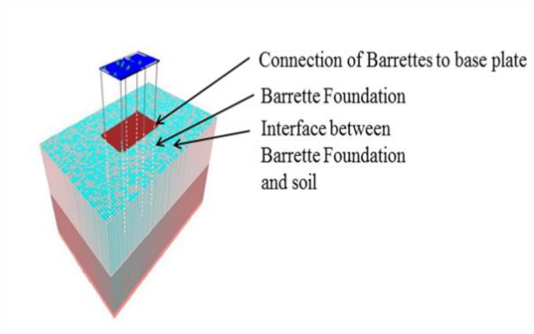


(h) Fourier transform for Chile Earthquake

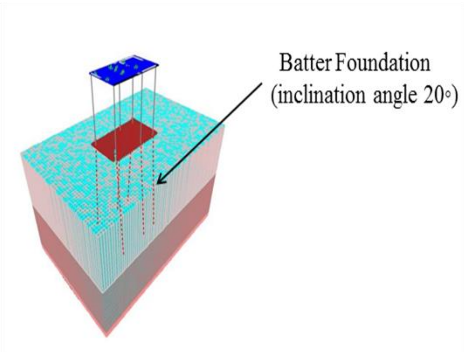
Fig. 4 Time history and Fourier transform for the input seismic excitations



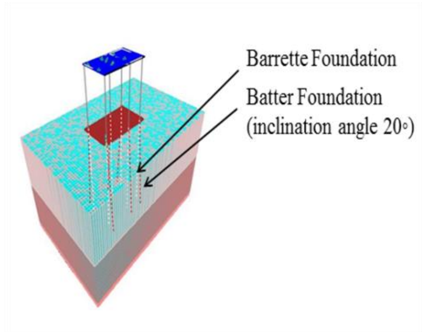
(a) Turbo generator foundation with raft



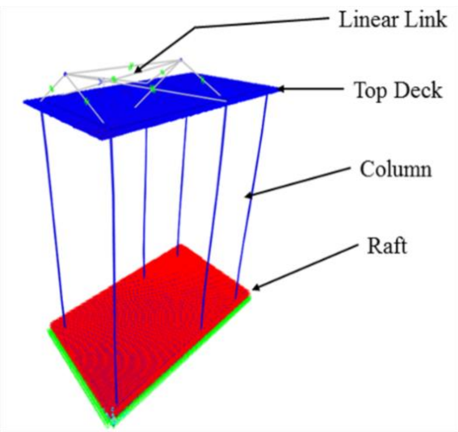
(b) Turbo generator foundation with raft and barrettes



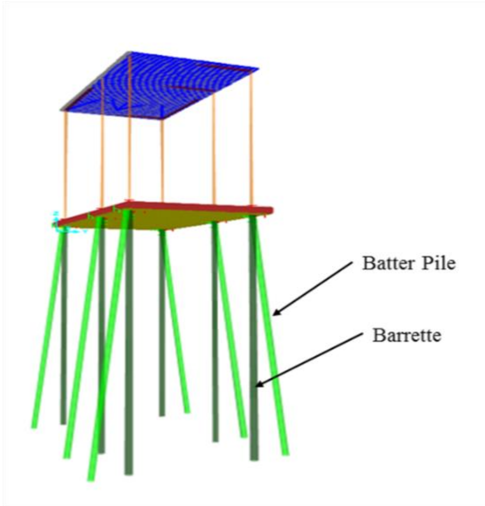
(c) Turbo generator foundation with raft and batter Pile



(d) Turbo generator foundation with raft, barrettes and batter Pile



(e) Turbo generator foundation model in SAP 2000 (scaling factor 1:34) without soil



(f) Turbo generator foundation model in SAP 2000 with raft, barrette and batter Piles without soil

Fig. 5 Model components of turbo generator foundation along with soil media in SAP 2000

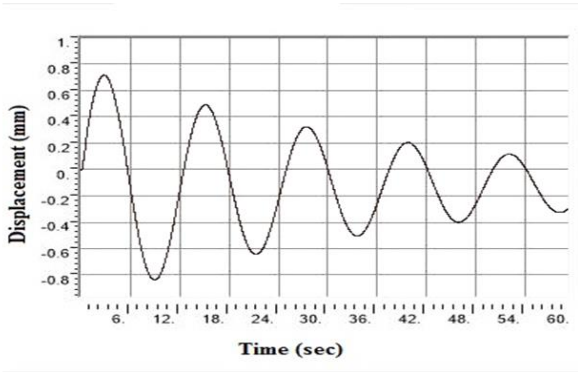
boundary conditions. Rotors of turbine are designed as rigid links to transfer the harmonic load and axial load. The vibration occurs in the foundation are due to the harmonic loads generated from the machine. The unbalanced forces are due to weight of the motor and the RPM. Sine functions are added to model the harmonic dynamic loads of the machine. Barrettes and batter piles have been designed as frame elements. The snapshots of the numerical models for raft, raft with barrette pile, raft with batter pile and raft with barrette and batter piles are given in Fig. 5. Horizontal displacements have been observed in the top deck and the maximum displacement values were plotted against time.

3. Results and discussion

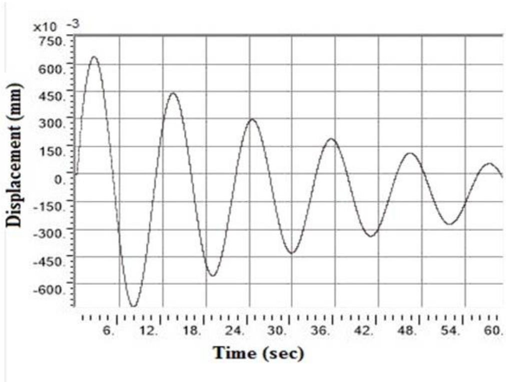
3.1 Displacement at top deck

The horizontal displacement value at top deck has been measured while the vibrator is oscillating and North ridge Earthquake (1994), Napa earthquake (2014), Chile earthquake (2015) and El-Centro earthquake (1940) has been assigned to the model. For numerical work the displacement (Horizontal) values has taken near the sine loading of the Top deck above the columns and shown in Fig. 6. Table 3 shows the horizontal displacement values of

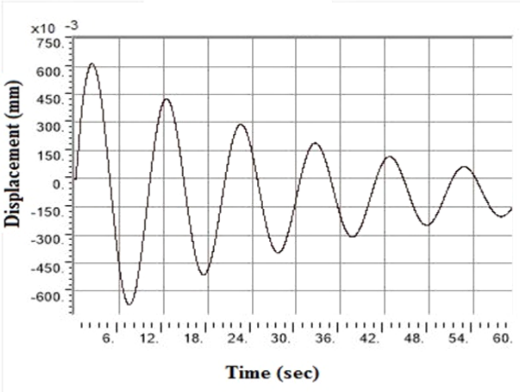
(a)Northridge Earthquake (0.901 (g))



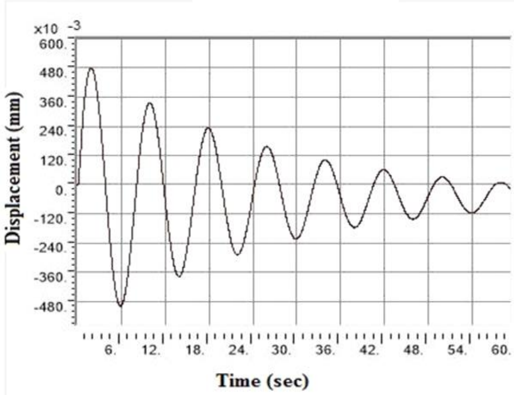
(i) Turbo generator foundation with only raft



(ii)Turbo generator foundation with raft-barrettes

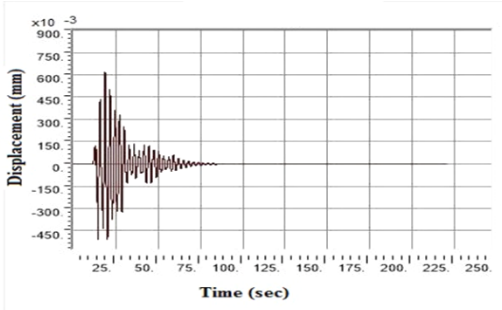


(iii) Turbo generator foundation with raft-batter pile combination

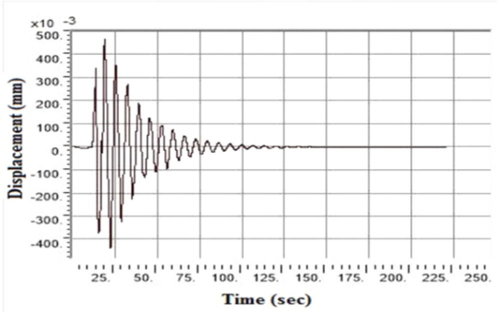


(iv) Turbo generator foundation with barrettes and batter pile with raft

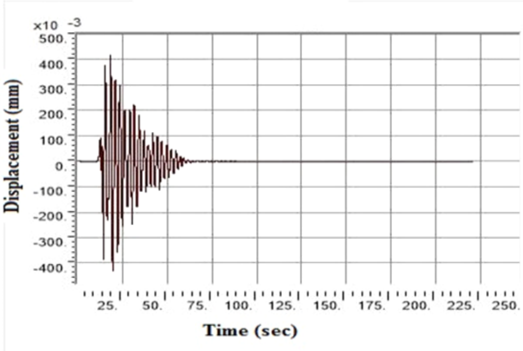
(b)Napa Earthquake (0.611(g))



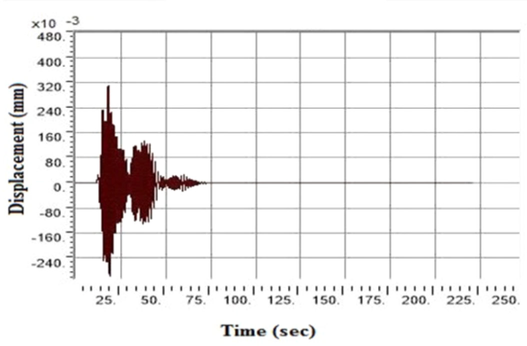
(i) Turbo generator foundation with only raft



(ii)Turbo generator foundation with raft-barrettes



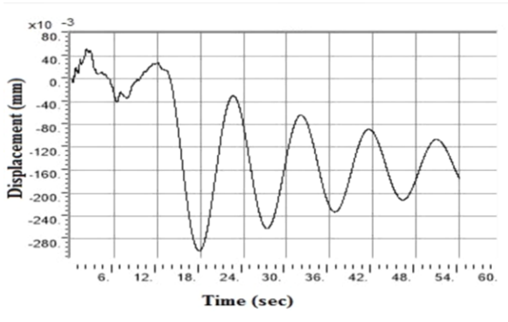
(iii) Turbo generator foundation with raft-batter pile combination



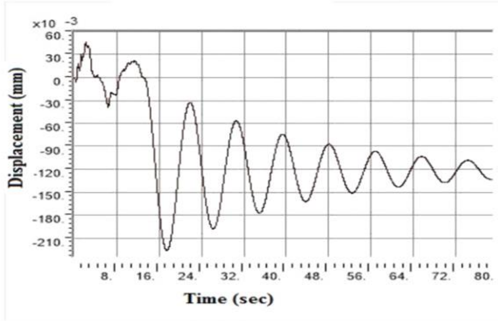
(iv) Turbo generator foundation with barrettes and batter pile with raft

Fig. 6 Maximum Displacements in Ux direction at top deck of the numerical model when subjected to earthquake loading

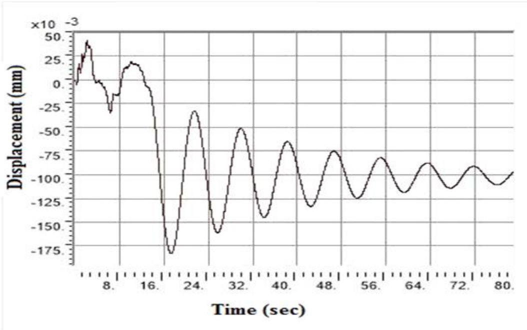
(c) El-Centro Earthquake (0.359(g))



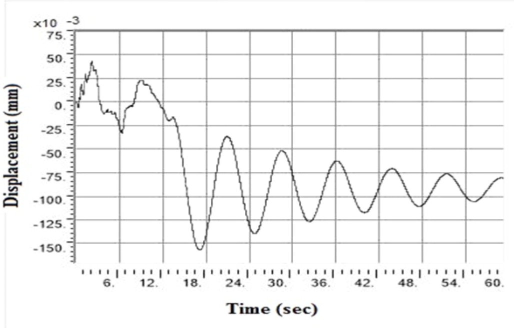
(i) Turbo generator foundation with only raft



(ii)Turbo generator foundation with raft-barrettes

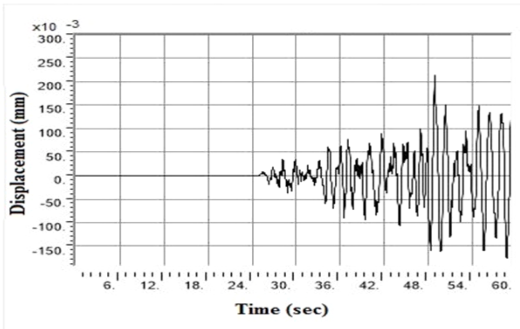


(iii) Turbo generator foundation with raft-batter pile combination

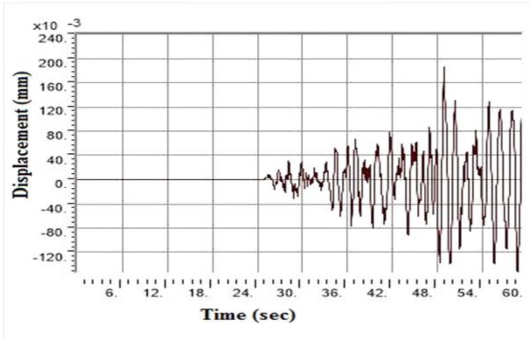


(iv) Turbo generator foundation with barrettes and batter pile with raft

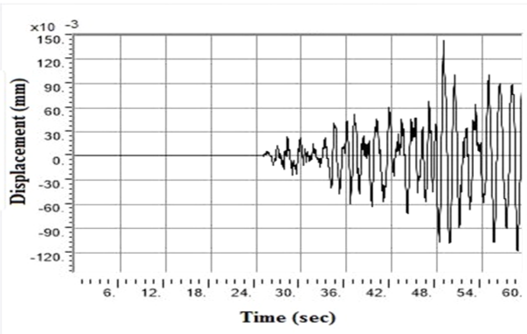
(d) Chile Earthquake (0.272(g))



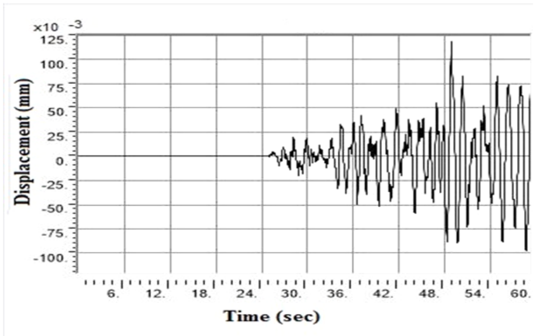
(i) Turbo generator foundation with only raft



(ii)Turbo generator foundation with raft-barrettes



(iii) Turbo generator foundation with raft-batter pile combination



(iv) Turbo generator foundation with barrettes and batter pile with raft

Fig. 6 Continued

different cases for both the experiment and numerical analysis. Both the experimental and numerical analysis results for the turbo generator foundation with raft, barrettes, batter pile and barrettes with batter pile predict closely matching displacement values for each of the analysed cases. It can be seen from Fig. 7 that there is a steady decrease in the displacement values for the foundation considered with raft-barrette, raft-batter and

Table 3 Displacement values from the experimental and computational model for turbo generator foundations raft, pile and barrettes

Horizontal Displacement Value(mm)					% difference between experimental and computational results
North ridge Earthquake (0.901 (g))					
Types of Foundation	**Experimental Work**	**% decrease**	**Computational Work**	**% decrease**	
Raft	0.820	--	0.838	--	2%
Raft-Barrette	0.700	15%	0.722	14%	3%
Raft-Batter	0.653	20%	0.672	20%	3%
Raft-Barrette with Batter	0.502	39%	0.500	40%	0%
***Napa* Earthquake (0.611(g))**					
Types of Foundation	**Experimental Work**	**% decrease**	**Computational Work**	**% decrease**	
Raft	0.630	--	0.620	--	1.6%
Raft-Barrette	0.482	23%	0.485	22%	0.6%
Raft-Batter	0.420	30%	0.419	32%	0.2%
Raft-Barrette with Batter	0.340	46%	0.337	46%	1%
***El-Centro* Earthquake (0.359(g))**					
Types of Foundation	**Experimental Work**	**% decrease**	**Computational Work**	**% decrease**	
Raft	0.310	--	0.3	--	3%
Raft-Barrette	0.224	27%	0.226	25%	1%
Raft-Batter	0.192	38%	0.19	36%	1%
Raft-Barrette with Batter	0.16	48%	0.155	48%	3%
***Chile* Earthquake (0.272(g))**					
Types of Foundation	**Experimental Work**	**% decrease**	**Computational Work**	**% decrease**	**% difference between experimental and computational results**
Raft	0.240	--	0.225	--	6%
Raft-Barrette	0.180	25%	0.183	26%	1.6%
Raft-Batter	0.145	40%	0.14	36%	3%
Raft-Barrette with Batter	0.126	48%	0.122	46%	3%

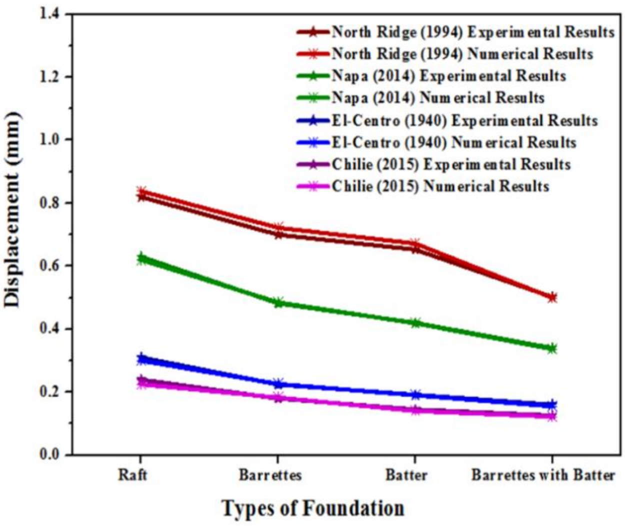
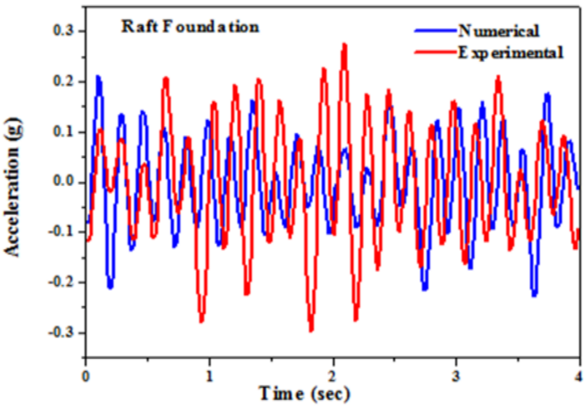


Fig. 7 Comparison of maximum displacement values of numerical and experimental work for different earthquakes

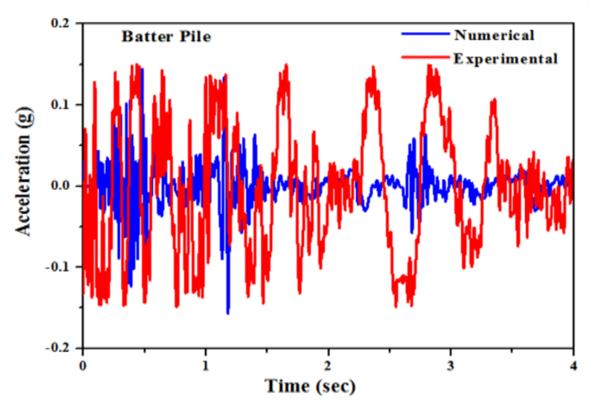
combination with raft-barrette and batter piles compared to only raft. By providing the barrettes and batter (inclination angle 20°) pile in raft for turbo generator foundation the displacement values can be decreased to (15-25%) and (20-40%) respectively. Further reduction of displacement values at top deck can be obtained by using both barrettes and batter piles along with raft on soft or poor soil.

3.2 Acceleration at top deck

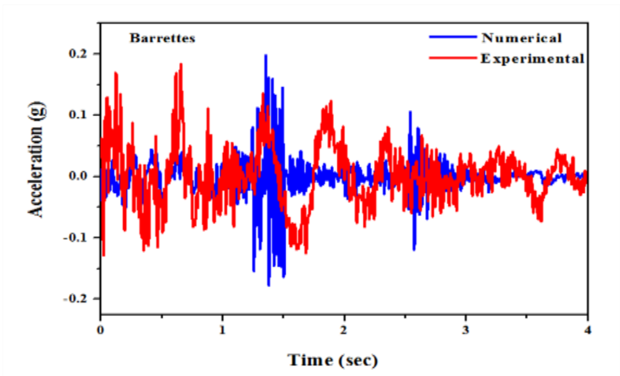
Fig. 8 presents the acceleration values at the top deck of the turbo generator model foundation for the raft, raft with barrettes, raft with batter pile and raft with barrettes and batter pile under the influence of sine loading of vibrator and subjected to North ridge earthquake conditions. Both experimental and the computational results indicate that the acceleration values at top deck obtained from SAP 2000 are in agreement with the measured data from shake table experiments. Figs. 9(a) and 9(b) show response spectra



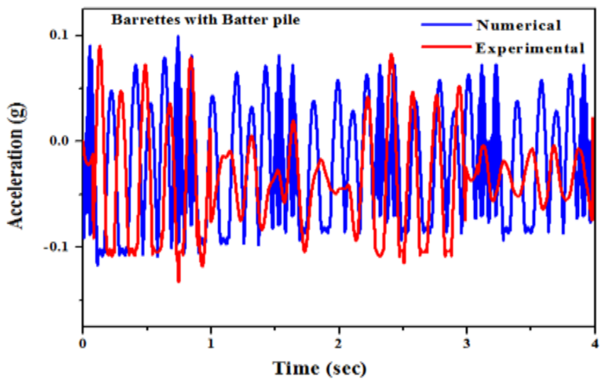
(a) Raft Foundation



(b) Raft-Batter Pile foundation

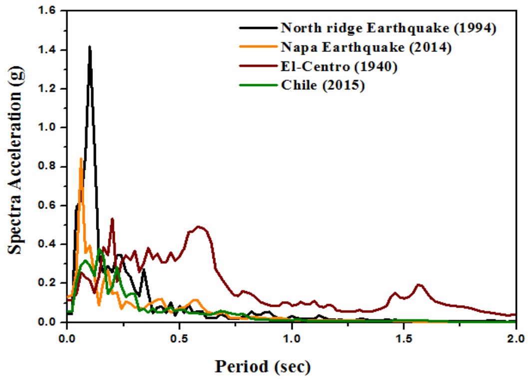


(c) Raft-Barrette Foundation

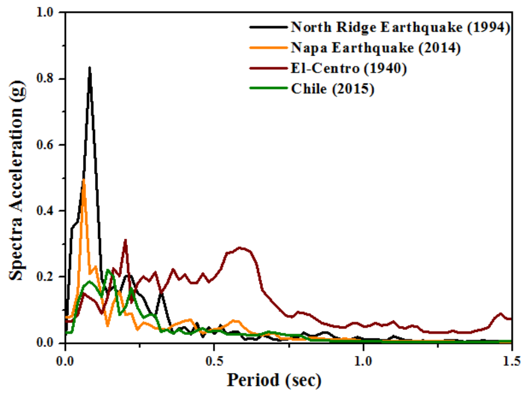


(d) Foundation with barrette and batter pile with raft

Fig. 8 Acceleration values at top deck of the turbo generator model foundation subjected to North Ridge Earthquake loading



(a) Turbo generator foundation with raft



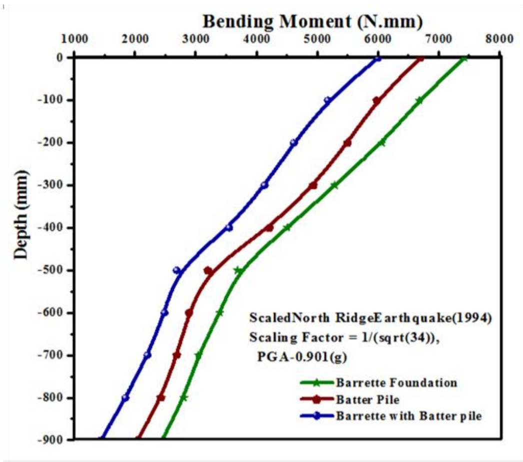
(b) Turbo generator foundation with raft, barrettes and batter pile

Fig. 9 Response Spectra curve taken at bottom of the raft for turbo generator foundation

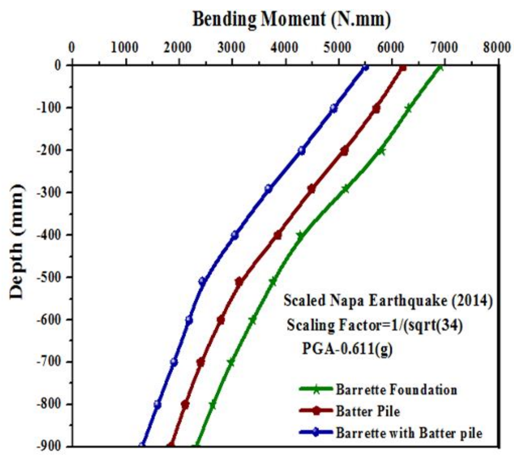
curves for the selected earthquake loadings applied at the bottom of the raft for turbo generator foundation. It can be observed that maximum value of spectra acceleration (g) for raft with the earthquake input motions North Ridge, Napa, EL-Centro, Chile are 1.42, 0.87, 0.46 and 0.32 respectively. By providing the barrettes and batter pile to the raft the spectra acceleration (g) value decreases to 0.83, 0.48, 0.3 and 0.21 respectively. Hence it can be concluded that 35-45% reduction in spectra acceleration values for the turbo generator foundations can be achieved by application of barrette with batter pile combination along with raft compared to the raft foundations.

3.3 Bending moment and horizontal displacement of barrettes/batter pile

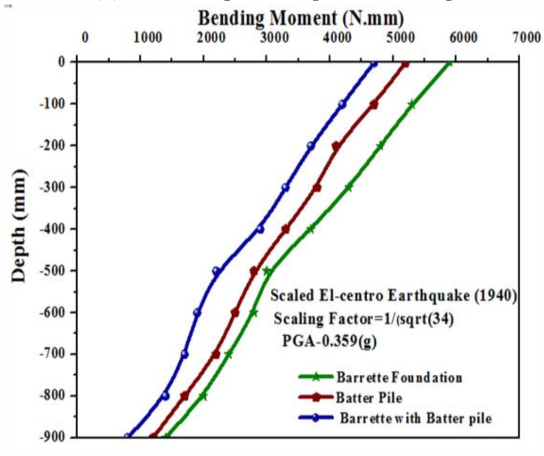
Fig. 10 shows the bending moment of barrettes, batter pile and barrette with batter pile during the shaking measured by the strain gauges which are installed on the pile at 10 cm interval. The bending moment distribution along the barrette/batter pile depths showed that the bending moments are highest at the top of the piles while gradually decreasing along the pile depth. Additionally it has been found that the combination of barrette and batter piles show the least bending moment compared to either of barrette and batter piles alone for all the earthquakes. The application of barrette and batter pile combination improves the mass



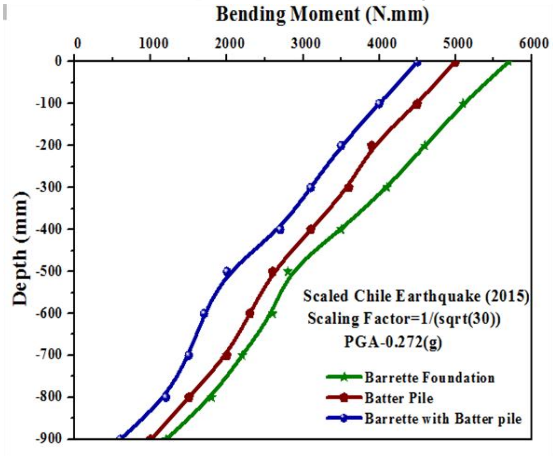
(a) Northridge earthquake loading



(b) Napa earthquake loading

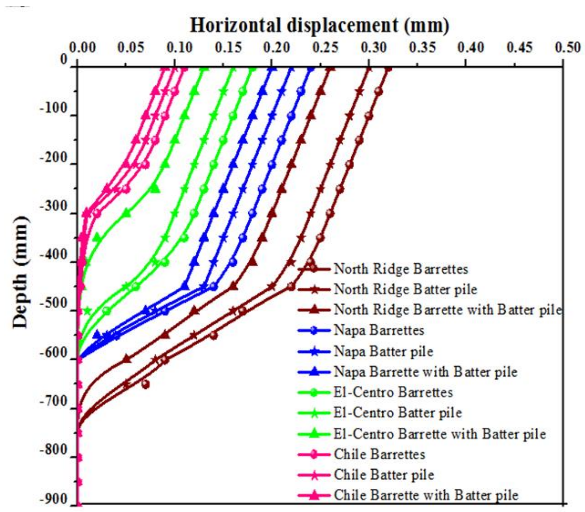


(c) El-Centro earthquake loading

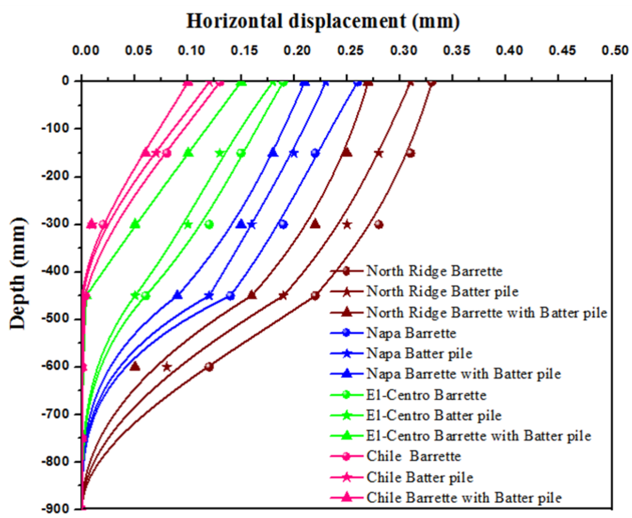


(d) Chile earthquake loading

Fig. 10 Bending moment distribution along barrette, Batter Pile, barrettes with batter pile under influence of different earthquake loading measured during shake table test



(a) Numerical analysis in SAP 2000

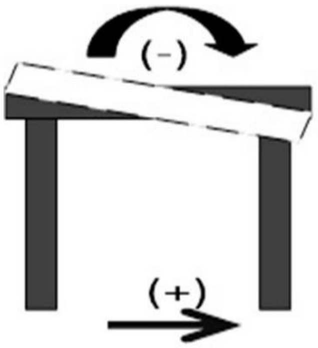


(b) Shaking table analysis

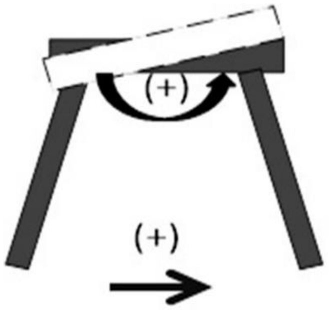
Fig. 11 Horizontal Displacement of barrette, batter Pile, barrettes with batter pile under earthquake loading: (a) Northridge (b) Napa (c) El Centro (d) Chile

distribution leading to less attraction of inertial force from same seismic excitation and thereby reduces the bending moment compared barrette/batter piles.

Fig.11 shows the horizontal displacement of barrettes/ batter piles under different seismic excitations. From the figure it can be observed that the combination of barrettes



(a) Rotation angle of barrettes



(b) Rotation angle of batter pile

Fig. 12 comparison of rotation angle of barrettes and batter piles

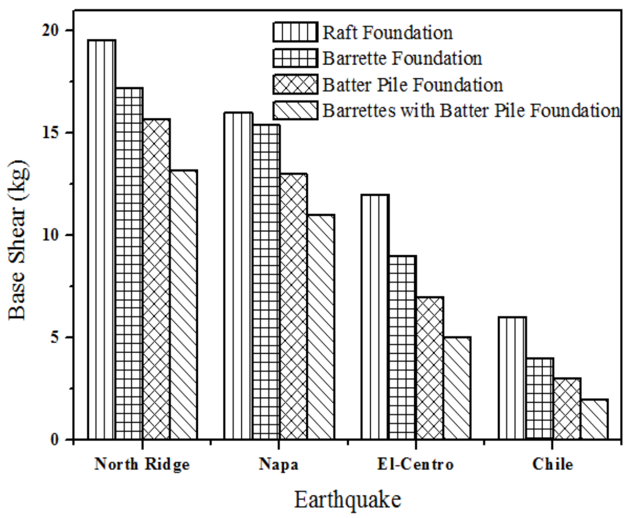


Fig. 13 Base shear for turbo generator foundation with raft, with barrette, with batter Pile and barrettes with batter pile obtained from computational analysis in SAP 2000

Table 4 Maximum Rotation Angle of the different foundations obtained from the Shake Table Experiment

Scaled earthquake acceleration record	Raft	Raft-Barrette	Raft-Batter	Raft-Barrette-Batter
North Ridge	28°	12°	24°	9°
Napa	24°	9°	19°	8°
El-Centro	15°	6°	13°	4°
Chile	16°	7°	14°	4°

with batter piles have low displacement values under the entire earthquake excitations. As the soil adopted for this experiment is sandy soil, its properties particularly degradation of stiffness with shear strain depends on confining pressure. Hence authors would like to highlight that the confining pressure values of sand cannot match reality due to small scale test in shake table even though the experimental results from the shake table test are closely matching with the predicted values from numerical model. However the shake table results can be used for reference purpose in correlating the earthquake intensity with the displacement and bending moment predictions.

3.4 Rotation angle

Rotation occurs when the inertial forces generated in a superstructure cause compression on one side and tension on the other side of the foundation, which in turn, results in settlement in one side and a possible uplift on the other side of the foundation, respectively. Hence, the rotation component plays an important role in the drift of the superstructure (Nguyen *et al*. 2016). The rotational angle has been calculated by dividing the difference of vertical displacement of raft at two ends with the length of raft. Fig. 12 explains the rotational movement of raft with barrettes and batter piles. In case of barrettes the moment and force (earthquake + vibrating load) counterbalance each other resulting very less rotational angle at top deck. But in the case of batter pile more rotational angle at top deck is observed. From Table 4 it can be observed that rotation angle of batter pile is more than the barrettes due to which more strain exists at the piles and more bending moment occurs at higher peak ground acceleration value (0.901 and 0.611 g), whereas for far field (lower value of g) smaller bending moment value occurs (Refer Fig. 10).

3.5 Base shear

Base shear is the maximum expected lateral force at the base of a structure due to seismic ground motion. It depends upon the site soil conditions, seismic ground motion and the fundamental period of vibration of the structure when subjected to dynamic loading. From Fig. 13 it is evident that the turbo generator foundations with barrette and batter pile combination have considerable less base shear compared to raft/barrette/batter piles.

4. Conclusions

Shake table tests were performed on turbo generator foundation model with raft, barrette, batter pile and combination of barrette and batter pile to determine the effects of the soil structure interaction under seismic loading. It was found that for higher magnitude earthquakes, the bending moment and horizontal displacement of batter piles increase as compared to barrettes. However, for low magnitude earthquakes batter piles have lower value of bending moment and horizontal displacement compared to barrettes. Barrettes with raft can be recommended for high seismic areas in poor soil conditions because it transfers seismic reaction through columns to barrettes thus increasing the stability and durability of the turbo generator foundation. Additionally barrettes have negligible effect on bending moments and horizontal displacement of foundation. Similarly for low seismic areas, batter piles with raft can be recommended in poor soil conditions but while designing care should be taken for proper reinforcing of piles with raft. However the shortcomings of batter pile can be avoided if it is used in combination with barrettes. Experimental results and computational model predictions recommend the combination of barrettes and batter piles with raft, for high seismic regions to achieve least vibration values in top deck and bottom pile, lowest bending moment and rotation angle of the foundation.

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